Gravity Control Measurements in North America

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INTRODUCTION

Cooperating in a joint program leading to an improved system of gravity control values in North America, the Coast and Geodetic Survey during 1952 and 1953 carried out pendulum measurements at eleven key stations in the United States, Canada, and Alaska. Two sets of the Brown Apparatus were employed, and new procedures were devised to reduce systematic temperature, magnetic, and sway effects which had become apparent following combined pendulum and gravity meter operations during 1950 and 1951. The measurement techniques and complete observational data are now being published to facilitate proper evaluation of the results with respect to other fundamental control data, and the eventual adoption of a uniform gravity standard.

The program was coordinated with observations by the Dominion Observatory of Canada using the Cambridge invar pendulum apparatus,[1] and with observations by the University of Wisconsin using the Gulf Research and Development Company modified quartz pendulum apparatus.[2] This enables direct comparison of the results of three independent systems at several widely spaced observation points, in conformity with recommendations of the Ninth General Assembly of the International Union of Geodesy and Geophysics, Brussels, 1951, and the International Gravity Commission, Paris, 1953.

The Alaska observations were carried out in 1952 under the direction of Lt. Norman E. Taylor. Pendulum stations were established at Umiat, Point Barrow, Fairbanks, Anchorage, and Kodiak. Gravity meter bases also were established at airports in McGrath, Bethel, Nome, Kotzebue, Seward, and Dutch Harbor. (See figs. 1 and 2.) The gravity meter results are included in this publication. At each observing site local connections were made by gravity meter to existing stations of other organizations. After standardization of the pendulums at Washington on June 30-July 1, the equipment was shipped to Seattle and the party then proceeded to Point Barrow, arriving on July 26. Pendulum observations were begun

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[1] Gravity measurements in North America with the Cambridge Pendulum Apparatus, by G.D. Garland, Parts I and II; Publications of the Dominion Observatory, Ottawa, Vol. 1, No. 12, 1953, and Vol. 1, No. 20, 1955.

[2] Report on gravity measurements carried out with the Gulf "M" and "K" sets of pendulums (1953-55), by J.C. Rose and G. P. Woollard; Technical report, Reference No. 56-72 (unpublished) Woods Hole Oceanographic Institution, 1956.

at Umiat on August 5 and concluded at Kodiak on September 8. All travel outside the United States was by air. Postseason standardizations were completed at Washington on October 8.

Observations in the United States and Canada were accomplished under the direction of Comdr. George R. Shelton in 1953 and comprised six stations over the gravity range between Brownsville, Tex. and Winnipeg, Manitoba (see fig. 1.) Preseason standardizations at Washington were completed on July 9 and field observations begun at Beloit, Kans. on July 22. During the course of the

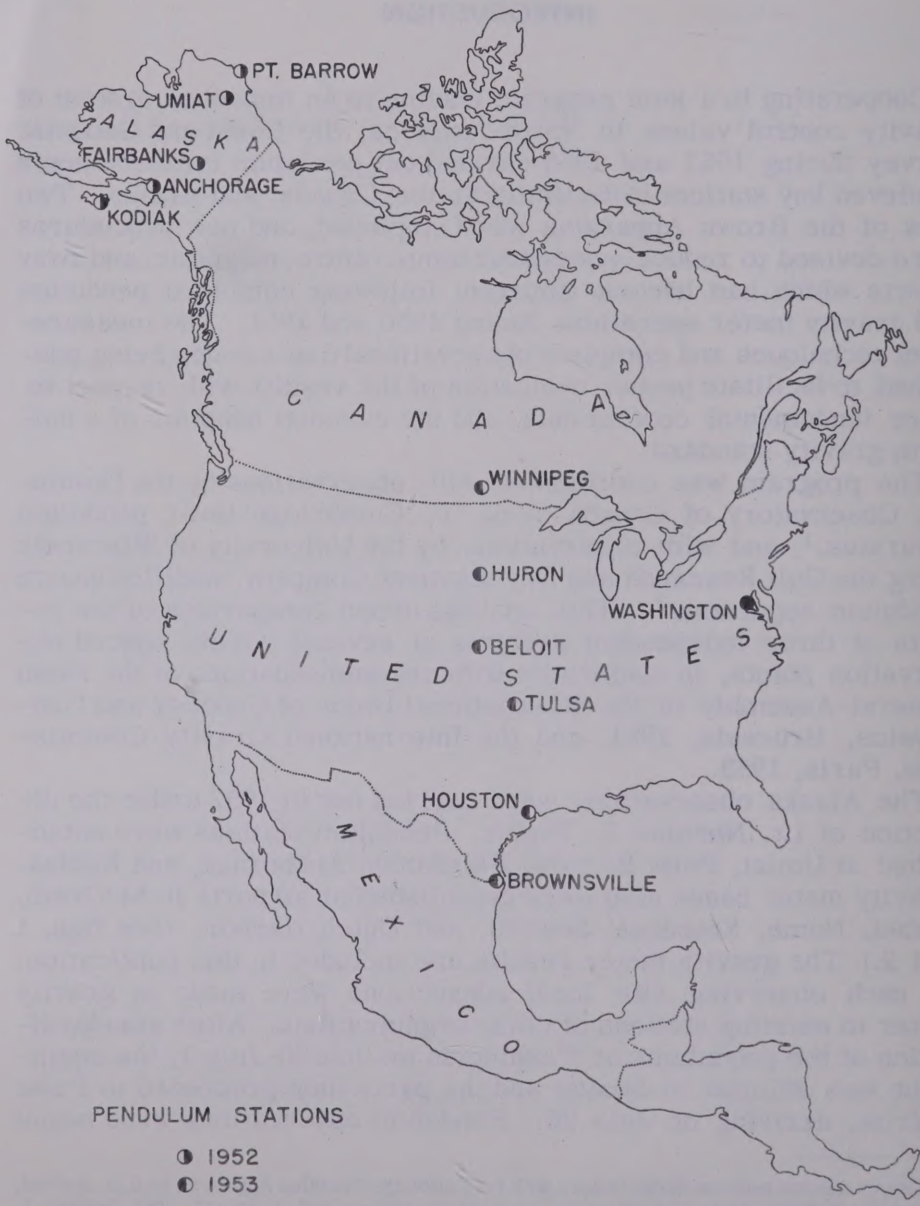

Figure 1.--Location of pendulum stations observed in 1952 and 1953.

measurements the Beloit station was occupied three times, permitting evaluation of consistency of both pendulums. The last field swings were made at Beloit on September 16 and postseason standardizations were completed on October 21. All transportation on this project was by truck.

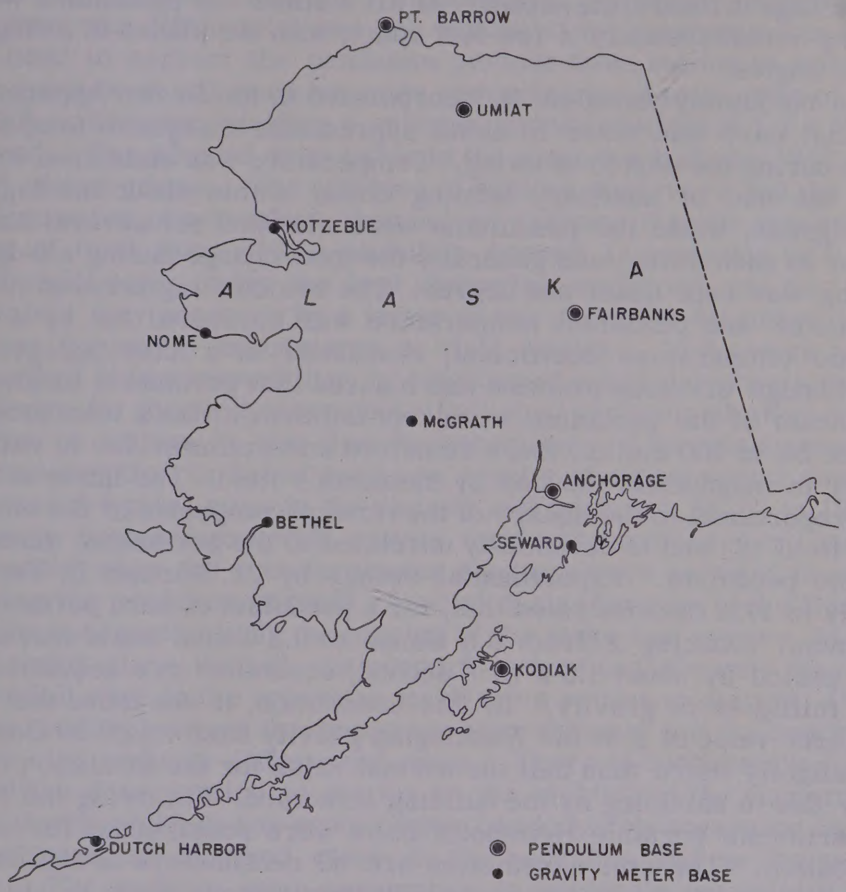

Figure 2.--Base stations established in Alaska, 1952.

PENDULUM OBSERVATIONS

Apparatus and Technique

Essential features of the Brown Apparatus are described in a previous publication.[3] This equipment superseded the Mendenhall type in 1932 and was designed especially to minimize the time required for setup and observations at field stations. The major changes included a device for clamping the pendulum during transportation and an improved method of timing the period of swing.

In the 1952-53 observations effort was made to minimize the systematic effects due to temperature changes, variation of the

[3] Pendulum gravity measurements and isostatic reductions, by Clarence H. Swick, U. S. Coast and Geodetic Survey Special Publication No. 232, U. S. Government Printing Office, Washington, 1942.

vertical component of the earth's magnetic field from station to station, and variable sway of the pendulum support. Two units of the Brown equipment were employed. These are designated Apparatus 2, containing invar pendulum B-8 and knife edge A-II; and Apparatus 3, containing invar pendulum A-8 and knife edge B-I. In each unit the agate plane is mounted in the pendulum head and the knife edge is fixed to the support. At all stations the pendulums were swung simultaneously a few feet apart, with the planes of swing at right angles.

As no dummy pendulum is incorporated in the Brown Apparatus, special care was taken to avoid appreciable changes of temperature during the period of swing. Temperature was stabilized without the use of auxiliary heating coils, within about one degree centigrade, while the pendulums were clamped for several hours prior to each swing, and generally the total change during a 6-hour swing was kept under one degree. The residual lag between thermometer and pendulum temperature was corrected for by a dynamic temperature coefficient, discussed in a later paragraph.

Although previous practice had insured that permanent magnetic moments of the pendulum were kept uniform within a tolerance of about 50 to 100 e.m.u., there remained uncertainties due to variations in magnetism induced by the earth's field. The latter effect is proportional to the square of the vertical component of the ambient field (Z) and is essentially unrelated to the permanent moment of the pendulum. Experimental swings by Lt. Norman E. Taylor early in 1952 demonstrated that, for a pendulum of zero permanent moment, reducing Z from 0.6 Gauss to 0.3 Gauss would increase the period by about 3.3×10^{-7} second, equivalent to a reduction of 1.3 milligals in gravity. In this connection, it was found that the ambient value of Z at the Washington gravity base was 0.30 Gauss, or slightly more than half the normal value for the locality, probably due to shielding by the building structure. Following the 1952 experiments portable Helmholtz coils were constructed for each pendulum. The coil assemblies are 60 centimeters in diameter, the planes of the coils spaced 30 centimeters apart by six demountable brass rods. After the base chambers are fixed in place by plaster, a magnetic dip needle is set up in the space to be occupied by the pendulum bob. Sufficient current is applied to the coil from a 6-volt storage battery to cause the needle to assume a horizontal position within a tolerance of about one degree. The dip needle is then removed, the pendulum apparatus installed, and the nullifying current maintained constant throughout the swings. These currents varied from about 80 milliamperes at Washington to 131 milliamperes at Point Barrow. Since there is practically no ferromagnetic material in the apparatus, other than the pendulum itself, the remaining magnetic effects are believed to be quite small. As an added precaution, however, the pendulums were tested for magnetism before beginning the swings at each station and demagnetized if the permanent moments exceeded 100 e.m.u.

Sway (or flexure) effects were minimized by maintaining, as nearly as possible, uniform conditions of support for the pendulum apparatus. At Washington the flush piers, at floor level, were used rather than the elevated piers to decrease the sway and to permit

more accurate interferometer readings. At other locations the apparatus was set up on firm concrete floors, usually in basements. Sway was measured before and after the pendulum observations at each station. Independent readings were taken by two or three observers at different swing amplitudes, and then reduced to a uniform amplitude of 5 millimeters. Contrary to previous practice, the differential sway as measured by interferometer was not used to correct the pendulum periods from station to station. The periods at all stations were corrected for a total sway of 1.2×10^{-5} millimeter, yielding a uniform period reduction of 7.1×10^{-7} second. The adopted sway value is the mean for both the 1952 and 1953 observations. The opinions of various observers and the interferometer observations themselves indicate that the measurement of total sway of the pendulum support is uncertain by 0.3×10^{-5} millimeter under the best observing conditions, and this uncertainty may increase by a factor of two under the vibration conditions frequently encountered at field stations. In the work here described it is assumed that, by selection of suitable concrete slabs or floors for the pendulum mounts, the actual variation of sway from station to station is less than the uncertainty of its measurement. The assumption is based partly on results of experimental swings at several typical sites in the vicinity of Washington, D. C. in 1952, wherein comparisons with gravity meter differences were more favorable when the interferometer readings were not used in correcting the pendulum periods. Special design features of the Brown Apparatus, particularly the placing of the large foot screws in the horizontal plane through the support, reduce considerably the differential sway in the apparatus itself from station to station. Uniform bonding between the apparatus base chamber and the concrete floor also reduces differential sway. There is undoubtedly some variation from station to station in the yielding of the supporting slab itself, which in any event cannot be adequately measured by an interferometer mounted close to the pendulum and on the same slab. The uniform sway assumption is obviously not valid if the base chamber is mounted in soil, in which case the measured sway may be much larger than its uncertainty and should therefore be applied as a correction.

The pendulum periods were measured by time intervals derived from the one-second pulses transmitted by National Bureau of Standards stations WWV near Washington, D. C., and WWVH on the Island of Maui, Territory of Hawaii. Normal time of the swings was 6 hours, plus or minus 5 or 10 minutes. There were a few exceptions, arising from channel interference, fadeouts, static, or temporary failure of the recording apparatus.

Corrections to reduce to zero amplitude, pressure, and sway were applied in accordance with the formulas and tables previously used for the Brown Apparatus.[4] Linear static and dynamic temperature coefficients for Apparatus 2 and Apparatus 3 were determined from experiments by Comdr. George R. Shelton in 1950.

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[4] Pendulum gravity measurements and isostatic reductions, by Clarence H. Swick, U. S. Coast and Geodetic Survey Special Publication No. 232, U. S. Government Printing Office, Washington, pp. 53-58, 1942.

The adopted coefficients for reducing the periods of invar pendulums A-8 and B-8 to the standard temperature of 15° C. are as follows:

Static, $(2.5 \pm 0.1) \times 10^{-7}$ sec./°C.

Dynamic, $(4.0 \pm 0.1) \times 10^{-7}$ sec./°C./hr.

The static temperature coefficient is based on a series of swings covering the range 19.5° to 25.1°C. This series did not involve the use of auxiliary heating coils, which were used in other phases of the 1950 experiments and caused anomalous variations in pendulum period. These variations were attributed to magnetic effects and strains set up in the pendulums by sudden heating or cooling. The dynamic temperature correction becomes appreciable when the rate of temperature rise or fall, as indicated by the thermometer in the pendulum case, exceeds about 0.2°C. per hour. At most stations the rate of temperature change was kept below this figure.

Observational Data

The complete observational records for each station are summarized in Tables I and II. Data are given for a 6-hour interval in each case, with the following exceptions: at Umiat the intervals of swing were 4, 5 1/2, 2, and 6 hours; at Fairbanks the interval for the third swing was 6 1/2 hours; at Brownsville the interval for the second swing was 6 1/2 hours. In computing the mean periods at Umiat the individual swings were weighted proportionally to the respective swing intervals.

Although not listed in the data summary, intermediate periods were determined at 2-hour intervals in accordance with previous practice to enable monitoring of pendulum performance. This also provided information on cumulative horizontal acceleration effects which are important in a single pendulum apparatus.

As mentioned in a preceding section, the corrected periods are calculated for a uniform total sway of 1.2×10^{-5} millimeter, rather than using the values measured by interferometer at each of the stations.

Standard deviations given in the final column of Tables I and II pertain to a single swing and enable estimation of internal consistency at the various sites. These figures adequately reflect observational precision, knife-edge stability, and horizontal vibration effects. Not represented are important systematic factors such as variable sway, pendulum changes, and possible errors at Umiat and Point Barrow arising from mean swing temperatures appreciably removed from the standardization range of 19.5° to 25.1° C.

Table I.—Pendulum observations in Alaska, 1952

Station	Date	Apparatus	Total arc Initial	Total arc Final	Mean pressure	Mean temperature	Temperature rate	Measured sway	Corrected period	Mean period	Standard deviation
			mm.	mm.	mm.	°C.	°C/hr.	10^{-5} mm.	10^{-7} sec.	10^{-7} sec.	10^{-7} sec.
Washington	June 30-July 1	2	7.74	4.04	2.0	29.75	-0.03	1.1	5008 892.8		
			7.89	4.06	2.0	28.28	-0.12		5008 893.7	5008 893.2	0.6
		3	9.08	5.35	5.8	29.89	-0.02	1.0	5009 693.7		
			9.15	5.42	5.8	28.28	-0.10		5009 696.0	5009 694.8	1.6
Umiat	Aug. 5-7	2	7.35	5.02	3.9	14.46	+0.12	1.4	5002 700.1		
			7.26	4.39	3.9	17.38	+0.25		5002 702.7		
			7.47	6.18	3.8	15.58	-0.75		5002 702.6		
			7.92	4.63	3.8	17.79	+0.55		5002 702.4	5002 702.0	1.0
		3	8.46	5.83	5.1	14.76	+0.02	2.2	5003 507.5		
			8.35	5.01	5.2	17.35	+0.24		5003 504.6		
			8.73	7.06	5.3	15.85	-0.70		5003 506.1		
			9.06	4.97	5.2	17.73	+0.53		5003 508.0	5003 506.6	1.4
Point Barrow	Aug. 10-13	2	7.86	4.44	4.7	14.45	0.00	1.6	5002 305.6		
			7.92	4.48	4.7	15.41	+0.02		5002 309.5		
			7.92	4.32	4.2	14.81	+0.08		5002 305.4		
			7.54	4.08	4.0	14.33	+0.07		5002 306.0	5002 306.6	1.9
		3	9.11	5.13	4.8	14.56	+0.02	1.5	5003 110.7		
			9.05	5.20	4.9	15.20	0.00		5003 110.3		
			9.14	5.15	4.9	14.47	+0.07		5003 105.4		
			8.65	4.73	4.8	14.28	+0.05		5003 110.1	5003 109.1	2.5
Fairbanks	Aug. 20-22	2	7.52	4.54	4.1	27.29	+0.35	1.0	5003 464.3		
			7.58	4.31	4.1	24.97	+0.37		5003 465.5		
			7.87	4.49	4.1	28.87	-0.03		5003 466.4	5003 465.4	1.0

Table I.—Pendulum observations in Alaska, 1952—Continued

Station	Date	Apparatus	Total arc: Initial	Total arc: Final	Mean pressure	Mean temperature	Temperature rate	Measured sway	Corrected period	Mean period	Standard deviation
			mm.	mm.	mm.	°C.	°C/hr.	10^{-5} mm.	10^{-7} sec.	10^{-7} sec.	10^{-7} sec.
Fairbanks (Con.)........		3	8.74	5.41	3.8	27.12	+0.35	0.9	5004 269.8		
			8.84	5.22	3.6	24.82	+0.43		5004 270.9		
			9.23	5.45	4.2	29.26	-0.05		5004 269.9	5004 270.2	0.6
Anchorage........	Aug. 29-31	2	7.91	4.49	4.0	22.83	+0.13	1.3	5004 240.8		
			7.76	4.42	4.0	22.45	+0.30		5004 241.1		
			7.50	4.26	4.1	24.72	-0.05		5004 242.2	5004 241.4	0.7
		3	9.13	5.33	4.1	22.71	+0.08	1.1	5005 047.7		
			8.85	5.18	4.1	22.24	+0.25		5005 046.0		
			8.73	5.08	4.6	24.42	0.00		5005 047.4	5005 047.0	0.9
Kodiak........	Sept. 6-8	2	7.37	4.23	3.5	20.53	+0.03	1.1	5004 732.4		
			7.72	4.31	3.5	20.59	+0.08		5004 732.3		
			7.64	4.34	3.6	21.51	+0.02		5004 733.0	5004 732.6	0.4
		3	8.66	5.47	3.0	20.98	+0.03	1.0	5005 538.1		
			8.85	5.57	3.0	21.12	+0.08		5005 537.4		
			8.94	5.48	3.0	22.02	+0.02		5005 538.6	5005 538.0	0.6
Washington........	Oct. 6-8	2	7.23	4.21	4.2	24.42	+0.03	1.3	5008 887.6		
			7.91	4.58	4.0	23.08	-0.03		5008 887.4		
			7.85	4.63	4.2	23.24	-0.18		5008 885.3	5008 886.8	1.3
		3	8.70	5.11	3.6	24.47	+0.08	0.7	5009 689.0		
			8.98	5.37	3.9	23.15	-0.13		5009 694.1		
			9.19	5.52	3.6	23.28	-0.17		5009 689.9	5009 691.0	2.7
							Mean Standard Deviation:				
									Apparatus 2		1.0
									Apparatus 3		1.5

Table II.—Pendulum observations in the United States and Canada, 1953

Station	Date	Apparatus	Total arc: Initial	Total arc: Final	Mean pressure	Mean temperature	Temperature rate	Measured sway	Corrected period	Mean period	Standard deviation
			mm.	mm.	mm.	°C.	°C/hr.	10^{-5} mm.	10^{-7} sec.	10^{-7} sec.	10^{-7} sec.
Washington........................	July 7-9	2	7.98	5.05	4.0	29.63	+0.13	1.0	5009 415.9		
			7.98	5.00	4.3	29.48	+0.03		5009 415.9		
			8.00	5.00	4.3	28.64	+0.05		5009 415.8	5009 415.9	0.1
		3	9.10	5.72	5.0	29.90	+0.12	1.1	5009 698.1		
			9.12	5.78	5.4	29.65	+0.03		5009 696.8		
			9.08	5.76	5.4	28.97	0.00		5009 694.6	5009 696.5	1.8
Beloit...........................	July 22-24	2	8.02	4.41	3.6	22.82	+0.08	1.2	5009 724.6		
			7.69	4.25	3.8	22.18	+0.05		5009 724.9		
			8.09	4.41	3.8	22.43	+0.03		5009 723.0	5009 724.2	1.0
		3	9.12	5.38	3.7	23.03	+0.10	1.4	5010 008.0		
			8.92	5.26	3.7	22.37	+0.03		5010 009.8		
			9.21	5.60	3.7	22.49	+0.02		5010 007.5	5010 008.4	1.2
Huron............................	July 30-Aug. 3	2	7.92	4.48	4.0	22.24	+0.08	1.5	5008 558.6		
			7.82	4.50	3.8	22.32	+0.08		5008 560.0		
			7.80	4.50	3.8	23.24	+0.08		5008 561.7		
			7.96	4.52	3.8	23.13	+0.03		5008 561.0	5008 560.3	1.4
		3	9.09	5.15	4.0	22.19	+0.08	1.3	5008 837.7		
			9.09	5.18	4.1	22.35	+0.07		5008 843.1		
			9.12	5.18	4.1	23.23	+0.07		5008 841.5		
			9.22	5.26	4.1	23.09	+0.03		5008 840.9	5008 840.8	2.3
Winnipeg.........................	Aug. 7-9	2	7.90	4.32	4.0	24.48	+0.07	0.9	5007 184.4		
			7.95	4.51	4.2	24.61	+0.02		5007 183.3		
			7.94	4.34	4.2	24.90	+0.03		5007 181.5	5007 183.1	1.5

Table II.—Pendulum observations in the United States and Canada, 1953—Continued

Station	Date	Apparatus	Total arc: Initial	Total arc: Final	Mean pressure	Mean temperature	Temperature rate	Measured sway	Corrected period	Mean period	Standard deviation
			mm.	mm.	mm.	°C.	°C/hr.	10^{-5} mm.	10^{-7} sec.	10^{-7} sec.	10^{-7} sec.
Winnipeg (Con.).....................		3	8.92	5.12	3.9	24.92	+0.08	0.8	5007 464.9		
			9.11	5.19	4.0	24.66	+0.02		5007 465.7		
			9.01	5.08	4.0	24.98	0.00		5007 465.2	5007 465.3	0.4
Beloit..............................	Aug. 17-19	2	8.12	4.49	4.0	23.71	- 0.02	1.5	5009 725.6		
			7.94	4.45	4.0	22.38	+0.07		5009 726.3		
			8.08	4.52	4.0	21.67	+0.07		5009 726.0	5009 726.0	0.4
		3	9.10	5.05	4.2	23.89	- 0.05	1.7	5010 006.2		
			8.89	5.20	4.2	22.48	+0.03		5010 005.8		
			9.08	5.24	4.2	21.83	+0.07		5010 006.5	5010 006.2	0.4
Tulsa...............................	Aug. 22-26	2	8.05	4.52	4.6	25.72	+0.08	1.2	5010 319.0		
			8.06	4.54	4.6	26.65	+0.23		5010 320.6		
			7.94	4.46	4.7	26.98	+0.12		5010 321.6		
			8.00	4.44	4.7	27.38	+0.17		5010 321.5	5010 320.7	1.2
		3	9.05	5.42	4.2	25.57	+0.08	1.3	5010 598.8		
			9.18	5.54	4.2	26.54	+0.18		5010 602.4		
			9.09	5.55	4.2	26.98	+0.10		5010 600.1		
			9.15	5.56	4.2	27.35	+0.13		5010 600.6	5010 600.5	1.5
Houston.............................	Aug. 29-31	2	7.88	4.46	4.2	25.36	+0.05	1.1	5011 515.6		
			7.70	4.41	4.2	24.98	+0.05		5011 515.9		
			7.96	4.42	4.2	25.07	+0.10		5011 517.1	5011 516.2	0.8
		3	8.86	4.82	4.4	25.44	+0.05	1.0	5011 797.4		
			8.82	4.90	4.5	25.01	+0.03		5011 798.1		
			9.05	4.94	4.5	25.01	+0.06		5011 797.5	5011 797.7	0.4

Table II.—Pendulum observations in the United States and Canada, 1953—Continued

Station	Date	Apparatus	Total arc		Mean pressure	Mean temperature	Temperature rate	Measured sway	Corrected period	Mean period	Standard deviation
			Initial	Final							
			mm.	mm.	mm.	°C.	°C/hr.	10^{-5} mm.	10^{-7} sec.	10^{-7} sec.	10^{-7} sec.
Brownsville........................	Sept. 3-5	2	8.04	4.90	2.6	29.53	+0.23	0.9	5012 179.8		
			8.05	4.52	2.6	29.10	- 0.04		5012 179.9		
			8.05	4.88	2.7	27.47	+0.03		5012 180.9	5012 180.2	0.6
		3	9.05	5.35	3.7	29.38	+0.18	0.7	5012 456.3		
			9.08	5.18	3.8	29.01	- 0.04		5012 457.0		
			8.98	5.39	3.8	27.49	+0.02		5012 454.8	5012 456.0	1.1
Beloit..............................	Sept. 14-16	2	8.00	4.30	4.3	22.72	+0.07	1.5	5009 727.7		
			8.02	4.28	4.3	21.23	+0.12		5009 727.2		
			8.00	4.26	4.3	20.86	+0.12		5009 726.3	5009 727.1	0.7
		3	8.88	4.71	6.6	22.79	+0.12	1.6	5010 007.3		
			9.10	5.16	4.8	21.32	+0.08		5010 005.6		
			9.06	5.02	4.9	20.82	+0.10		5010 004.3	5010 005.7	1.5
Washington.........................	Oct. 19-21	2	7.89	4.42	3.8	23.20	+0.13	1.4	5009 416.8		
			8.00	4.52	3.8	22.83	0.00		5009 417.7		
			8.02	4.48	3.8	22.80	0.00		5009 417.8	5009 417.4	0.6
		3	9.02	5.65	4.0	23.35	+0.10	1.4	5009 699.3		
			9.04	5.62	4.2	22.96	- 0.02		5009 698.7		
			9.00	5.61	4.1	22.82	- 0.03		5009 696.7	5009 698.2	1.4
							Mean Standard Deviation:				
							Apparatus 2				0.8
							Apparatus 3				1.2

Discussion of Errors

The various observational parameters are tabulated below, with estimated standard deviations of each and their corresponding effects on the corrected periods:

	Estimated error	Δ Period 10^{-7} sec.
Arc	0.025 mm. (in initial and final arcs)	0.21
Mean pressure	0.2 mm	0.32
Mean temperature	0.1°C	0.25
Timing	1.5×10^{-3} sec.	0.38
	Resultant	0.6×10^{-7} sec.

Some of the difference between calculated and observed standard deviation of a swing may be ascribed to the kinetic disturbances which seem to affect nearly all pendulum observations, but the greatest contribution undoubtedly comes from external horizontal accelerations not inherently balanced out in a single pendulum apparatus. This difficulty is reduced but not eliminated in a 6-hour swing. Nevertheless, the observed standard deviation seems to set reasonable limits on the mean horizontal acceleration effects for a single swing, namely 1.1×10^{-7} and 0.8×10^{-7} second, respectively, for the 1952 and 1953 observations. In summary, the average random error of mean period of a pendulum at a station seems to be somewhat less than 1.0×10^{-7} second, a satisfactory figure. To this must be added the uncertainty due to sway variations which are too small to be accurately detected by interferometer observations at field stations. The uncertainty cannot be estimated closely with confidence, but a safe average value may be taken as 1.5×10^{-7} second, with the maximum hardly exceeding 2.5×10^{-7} second. These figures roughly correspond to average and maximum deviations in total sway of 0.2×10^{-5} and 0.4×10^{-5} millimeter, respectively. The unusually high values for measured sway at Umiat and Point Barrow are probably due to vibrations from local machinery which seriously affected the interferometer readings. These vibrations may also have reduced somewhat the accuracy of the measured periods.

An additional error source is the possible alteration in inherent period of a pendulum, either from dimensional change or some less obvious cause, as the apparatus is transported between stations. With the Brown Apparatus this source combines with the sway uncertainty to produce irregularities in the comparisons between pendulums from station to station and also in reoccupation of stations with the same pendulum.

Over-all reliability is thus critically dependent on two dominating factors, namely sway variation and inherent period stability.

Summary of Results

1952 Season

Pendulum gravity differences with respect to the Washington base site are given, based on the mean of pre- and post-season

standardizations at Washington and the mean of the corrected periods at field sites.

Observed Gravity Differences (mgals)

Station	Base	App. 2	App. 3
Umiat......................	Washington (1,2)	+2426.2	+2425.1
Point Barrow............	Washington (1,2)	+2581.5	+2581.3
Fairbanks................	Washington (1,2)	+2126.4	+2125.3
Anchorage.....	Washington (1,2)	+1821.8	+1820.4
Kodiak	Washington (1,2)	+1629.0	+1627.8

It will be noted that Apparatus 2 showed a period decrease of 6.4 x 10^{-7} second between the two Washington standardizations; this was about twice the expected maximum change. After completion of the postseason swings the seals of both pendulum units were opened and the pendulums examined. A fine crack was found in the agate plane of Apparatus 2, extending about one-third the width of the plane. Although this crack had not come in contact with the knife edge, a slight period change would be expected due to alteration in the effective pendulum length. Making allowance for the generally unfavorable conditions at Umiat and Point Barrow, the internal performance of Apparatus 2 apparently was not greatly affected by the damaged agate plane at any of the stations. There is strong indication, however, that the pendulum period changed sometime after the preseason swing at Washington on July 1, and stabilized sometime before the occupation of Fairbanks on August 20, remaining stabilized through the postseason swings at Washington. If only the postseason standardization is used for Apparatus 2, the results fall into excellent agreement with the Apparatus 3 values for Fairbanks, Anchorage, and Kodiak, giving differences of +0.2, -0.1, and +0.1 milligal, respectively. However, as the time of damage could not be definitely determined it was decided to base the 1952 field values solely on Apparatus 3, with the added consideration that results are supported by a reasonable interpretation of the performance of Apparatus 2. The adopted results are:

Gravity Values*

Referred to Commerce Base, g = 980.118 gals

Station	g (Pendulum site)
Washington	980.1182
Umiat........	982.5433
Point Barrow.................................	982.6995
Fairbanks.....................................	982.2435
Anchorage....................................	981.9386
Kodiak...	981.7460

*From Apparatus 3 measurements only.

Observing conditions were very satisfactory at Fairbanks, Anchorage, and Kodiak, and the derived gravity values appear reliable within one milligal at these stations. The values for Umiat and Point Barrow may be in error by as much as 1.5 milligals due to various unavoidable conditions, such as poor time-signal reception, low observing temperatures, relatively unstable pendulum supports, and severe local vibrations.

In computing the 1953 gravity differences Beloit was used as an intermediate base, in view of the apparent progressive change in periods of both pendulums at the three occupations of this station. Thus three Washington-Beloit differences were computed, as based on the mean of the pre- and post-season swings at Washington and on the three Beloit occupations computed separately. The final Washington-Beloit difference was taken as the mean of these three. Values for other stations were then determined with reference to Beloit, employing the two appropriate base occupations at that station. Resulting gravity differences and means for the two pendulums are:

Observed Gravity Differences (mgals)

Station	Base	App. 2	App. 3	Mean
Beloit (1).............	Washington (1,2)	-120.4	-121.7	-121.0
(2).............	Washington (1,2)	-121.1	-120.8	-121.0
(3).............	Washington (1,2)	-121.5	-120.6	-121.0
Huron..................	Beloit (1,2)	+455.9	+456.5	+456.2
Winnipeg..............	Beloit (1,2)	+995.3	+995.2	+995.2
Tulsa..................	Beloit (2,3)	-232.4	-232.5	-232.4
Houston................	Beloit (2,3)	-699.7	-700.6	-700.2
Brownsville...........	Beloit (2,3)	-959.2	-957.8	-958.5

The adopted values as shown below reflect the straight mean of measurements with the two pendulums.

Gravity Values

Referred to Commerce Base, $g = 980.118$ gals

Station	g (Pendulum site)
Washington............	980.1182
Beloit..................	979.9972
Huron....................	980.4534
Winnipeg...............	980.9924
Tulsa....................	979.7648
Houston.................	979.2970
Brownsville............	979.0387

The agreement between pendulums is generally satisfactory, assuming a progressive period increase for Apparatus 2 and a decrease for Apparatus 3 as indicated by the three occupations at Beloit. This assumption is supported to some extent by the Washington pre- and postseason periods for Apparatus 2. However, Apparatus 3 shows a net decrease of 2.7×10^{-7} second in its period at Beloit and an increase of 1.7×10^{-7} second at Washington. Also, the interpendulum agreement is noticeably poorer at Brownsville than at the other stations. These factors indicate that the results are sometimes subject to uncertainty from causes other than random measurement errors and simple changes in effective length of the pendulums. As mentioned in a preceding section, small variations in sway are quite probably the major remaining sources of uncertainty.

Assuming the determinations with Apparatus 2 and Apparatus 3 to be completely independent, the average value of mean square error for a gravity difference is approximately 0.5 milligal. This is probably a slight underestimate of the true error, in view of

possible correlation between results of the two pendulums at the same station. Such a correlation would occur if abnormal sway effects were similar for both pendulum installations.

The major contribution to calculated uncertainty is a discrepancy of 1.4 milligals between the two pendulums at Brownsville. No reason for this was found, but it was noticed that at this station the manometer pressures recorded for Apparatus 2 on all three swings were about 40 percent less than usual. Application of the normal pressure in correcting the periods would reduce the inter-pendulum discrepancy to 0.4 milligal. However, there was no evidence of faulty operation of the manometer and the Apparatus 2 results at Brownsville are accepted at face value.

GRAVITY METER OBSERVATIONS IN ALASKA

Measurement Procedure

During the course of the pendulum measurements in Alaska subsidiary stations were established by gravity meter at six outlying locations to control future surveys. These points were connected to the pendulum stations at Fairbanks and Anchorage, making use of air transport as available. Gravity differences were determined by large-dial readings on Worden gravity meter No. 114. As a general practice the drift loops were corrected only for time of travel between stations, thus eliminating the extensive layover periods sometimes imposed by transport schedules and other duties. The stations at McGrath, Bethel, Nome, and Kotzebue were measured in one continuous drift loop based on Fairbanks, permitting duplicate occupations at all but the outermost station. Seward and Dutch Harbor were individually connected to Anchorage using loops of the type A-B, B-A. The latter type of connection was also employed in measuring between the pendulum stations to obtain a meter calibration over the range covered by the subsidiary stations. The observational data are listed in Table III.

Table III.--Observational Data, Worden Meter No. 114

Connection	Time hrs.	Dial Difference: Observed	Dial Difference: Corrected for drift	Dial Difference: Mean	Dial Difference: Drift mgal/hr.
Umiat-Fairbanks	6.1 6.1	-40.965 +41.104	-41.035	-41.035	+0.083
Umiat-Pt. Barrow	3.8 4.7	+21.597 -21.445	+21.529	+21.529	+0.131
Fairbanks-McGrath	4.3 4.2	-15.897 +16.077	-16.001 +15.975	-15.988	+0.177
Fairbanks-Bethel	6.6 6.7	-33.128 +33.431	-33.288 +33.268	-33.278	+0.177
Fairbanks-Nome	10.3 9.6	+4.278 -3.841	+4.028 -4.074	+4.051	+0.177
Fairbanks-Kotzebue	13.4 13.9	+23.376 -22.713	+23.051	+23.051	+0.177

Table III.—Observational Data, Worden Meter No. 114—Continued

Connection	Time hrs.	Dial Difference: Observed	Corrected for drift	Mean	Drift mgal/hr.
Anchorage-Seward..................	4.0 2.8	-0.820 +0.928	-0.884	-0.884	+0.115
Anchorage-Fairbanks................	4.2 4.7	+41.989 -41.842	+41.920	+41.920	+0.120
Anchorage-Kodiak....................	4.0 3.7	-26.532 +26.694	-26.616	-26.602	+0.153
	5.7 6.0	-26.495 +26.687	-26.589		+0.120
Anchorage-Dutch Harbor............	8.5 8.9	-53.025 +53.341	-53.179	-53.179	+0.132

Meter Calibration

As Worden meter No. 114 had just been received from the manufacturer the large-dial calibration was uncertain, especially for the Alaska gravity range. Consequently a calibration was determined by least-squares adjustment employing the four pendulum gravity differences between Kodiak and Point Barrow. An observation equation was written for each difference in the conventional manner, except that the Fairbanks-Umiat and Umiat-Point Barrow equations were assigned half weight because of the greater uncertainty in the Umiat and Point Barrow pendulum values. The results are summarized below:

	Residual (mgals)
Kodiak-Anchorage..................................	-0.95
Anchorage-Fairbanks..............................	-0.18
Fairbanks-Umiat....................................	+1.22
Umiat-Pt. Barrow..................................	-0.44

Scale constant (LDK) = 7.277 $\pm$ 0.011 mgals/division

The precision of the computed scale constant appears consistent with various uncertainties present, such as pendulum errors, drift, and the minor irregularities known to exist in large-dial readings of the meter. The adjusted scale constant was verified to one part in 1,000 in tilt-table measurements taken by the gravity party at Point Barrow and Anchorage during August, 1952.

Data Summary

Deduced gravity meter values for the subsidiary stations as referred to Commerce Base, $g = 980.118$ gals, are:

Station	Gals
McGrath..	982.1272
Bethel..	982.0013
Nome...	982.2730
Kotzebue..	982.4112
Seward...	981.9322
Dutch Harbor.....................................	981.5516

Connections to Nearby Stations

Local gravity differences were measured to various existing stations, employing the small dial of Worden meter No. 114. The connections listed below have a mean square error of less than 0.1 milligal as indicated by duplicate measurements:

From	To	Gravity difference (mgals)
Umiat..........................	Umiat airstrip (Woollard, 1950)	+0.89
Point Barrow...............	Point Barrow airstrip (Woollard, 1950)	+0.30
Fairbanks	Geophysical Institute (Garland, 1953)	+1.76
Anchorage..................	Elmendorf AFB, passenger lobby (Woollard, 1950)	- 1.60
Dutch Harbor...............	Unalaska Pendulum (USC&GS, 1938)	- 3.78

DESCRIPTIONS

Pendulum Stations

Washington. The two sets of apparatus were set up on the flush piers, at floor level, in the gravity room of the Commerce Building between Fourteenth and Fifteenth Streets NW., Washington, D. C. The gravity value on the flush piers is 0.18 milligal greater than at the top of the west elevated pier, which is defined as the Commerce Base.

Latitude, 38° 53'.6; longitude, 77° 02'.0; elevation, 0.2 meter.

Umiat. At Umiat, Alaska, in the southwest corner of the dravo (heater) room of Building 20, about 200 yards southwest of the airstrip and west of the road leading from the airstrip to the camp. Pendulum site is marked by a standard USC&GS gravity disk (unstamped), set in a drill hole.

Latitude, 69° 22'.1; longitude, 152° 08'.7; elevation, 107.3 meters.

Point Barrow. At Point Barrow, Alaska, in the Butler Building which is directly south of Building 252. The building is supported by pilings which were steamed into permafrost, and the floor is about 3 feet above ground level. Pendulum site is marked by a standard USC&GS gravity disk stamped PT BARROW 1952, in the southwest corner of the concrete floor.

Latitude, 71° 19'.6; longitude, 156° 40'.6; elevation, 3.4 meters.

Fairbanks. At Ladd Air Force Base, Fairbanks, Alaska, in the basement of Building 1157 (BOQ No. 10), in the washroom at the southwest corner of the basement. Pendulum site is marked by a standard USC&GS gravity disk cemented in the concrete floor, stamped FAIRBANKS 1952.

Latitude, 64° 50'.7; longitude, 147° 36'.2; elevation, 135.2 meters.

Anchorage. At Elmendorf Air Force Base, Anchorage, Alaska, in the basement and mechanical room (boiler room) of VOQ Building 10-430, in the southeast corner of the concrete floor. Pendulum site is marked by a standard USC&GS gravity disk set in the floor.

Latitude, 61° 15'.2; longitude, 149° 49'.4; elevation, 48.1 meters.

Kodiak. At the Kodiak Naval Base, about 6 miles southwest of the town of Kodiak, Alaska. Station is in Building 17 (old engine test building), in a room between the two engine test sites, in the north end of the room at the foot of a concrete stairway. Pendulum site is marked by a standard USC&GS gravity disk stamped KODIAK 1952, set in the concrete floor.

Latitude, 57° 44'.5; longitude, 152° 30'.3; elevation, 11.4 meters.

Beloit. At Beloit, Kans., in the basement of a service station operated by Mr. J. Sault, at the northeast corner of South Brooklyn Street and Asherville Road. The pendulum site is on the east side of the westerly basement room. A standard USC&GS gravity reference disk, set in a circular concrete post 10 inches in diameter and stamped BELOIT 1950, is in a north-south fence line about 230 feet north-northeast of the

pendulum site. The gravity meter difference from pendulum site to reference disk is minus 0.56 milligal.

Latitude, 39° 27!3; longitude, 98° 06!2; elevation, 418.2 meters.

Huron. At Huron Airport, about 1.2 miles north of the railroad station at Huron, S. Dak., in the basement furnace room of the Administration Building. The pendulum site is near the south wall of the building and about 20 feet from the east wall. A standard USC&GS gravity reference disk, set in the concrete step to east door of hangar, is approximately 220 feet east of the pendulum site. The gravity meter difference from pendulum site to reference disk is minus 0.53 milligal.

Latitude, 44° 23!0; longitude, 98° 13!4; elevation, 389.6 meters.

Winnipeg. In Winnipeg, Manitoba, in the basement of the Dominion Public Building on Main Street, on the westerly side of Room 2.

Latitude, 49° 53!4; longitude, 97° 08!3; elevation, 229.5 meters.

Tulsa. In Tulsa, Okla., at the University of Tulsa, in Room 4 of the Waite Phillips Engineering Building. The pendulum site is 28 feet from the south wall and 8 feet from the east wall. A standard USC&GS gravity station disk is at the southeast corner of the Engineering Building, one foot north of USC&GS bench mark J 137. The gravity meter difference from pendulum site to station disk is minus 0.15 milligal.

Latitude, 36° 09!3; longitude, 95° 56!5; elevation, 234.3 meters.

Houston. In Houston, Tex., in storeroom of the building at 2424 Branard Street occupied in 1953 by Houston Technical Laboratory but now occupied by Electro-Tech International Company. The pendulum site is about 5 feet from the east wall and 20 feet from the south wall of the storeroom. A standard USC&GS gravity station disk, stamped HOUSTON 1950, is set vertically in the wall of the building, one foot south of the northwest corner and one foot above ground. The gravity meter difference from pendulum site to station disk is minus 0.08 milligal.

Latitude, 29° 44!2; longitude, 95° 25!1; elevation, 18.4 meters.

Brownsville. In Brownsville, Tex., in Room B-10 of the basement of the U. S. Post Office. The basement floor is 11.0 feet below USC&GS bench mark K678 at the front entrance of the Post Office. The gravity meter difference from pendulum site to bench mark K678 is minus 0.78 milligal.

Latitude, 25° 54!1; longitude, 97° 30!0; elevation, 8.1 meters.

New Gravity Meter Stations, Alaska

McGrath. At the McGrath airstrip, on the concrete ramp to the maintenance garage south of the CAA building. Station is marked by a USC&GS azimuth disk set in the ramp, about level with the northwest-southeast runway. Disk is stamped McGRATH BASE 1951 NW.

Latitude, 62° 57!3; longitude, 155° 36!1, elevation, 98.1 meters.

Bethel. In Bethel, at the side of the north steps of the Weather Bureau building. Station is marked by a USC&GS reference disk stamped BENCH MARK PLUS 6.27, brazed to a pipe set in the ground. The disk is on the southerly edge of the taxi strip of the east-west runway and at the level of the runway.

Latitude, 60° 46!5; longitude, 161° 43!3; elevation, 7.3 meters.

Nome. In Nome, in the southwest corner of the concrete foundation of the flagpole in front of the Post Office and Court House building. Station is marked by a U. S. Engineer Office disk stamped BM T G 4 1944, cemented in a drill hole.

Latitude, 64° 29!9; longitude, 165° 24!2; elevation, 5.2 meters.

Kotzebue. In Kotzebue, about 15 feet back of and 6 feet above high water, marked by a USC&GS triangulation reference disk stamped ASTRO RM NO. 2.

Latitude, 66° 54!1; longitude, 162° 35!4, elevation, 1.8 meters.

Seward. In Seward, at the corner of Fifth and Adams Streets, 5 yards north of the southeast corner of the Federal Building, in the east face and at top of the concrete foundation. Station is marked by a USC&GS bench mark, stamped K 11 1923 and set vertically.

Latitude, $60^\circ\ 06'.2$; longitude, $149^\circ\ 26'.2$; elevation, 16.9 meters.

Dutch Harbor. At the southerly end of the Dutch Harbor airport, at the waiting room and weather station. The station (unmarked) is on a concrete walk about one foot south of the waiting room door and one foot east of the building wall.

Latitude, $53^\circ\ 54'.8$; longitude, $166^\circ\ 32'.3$; elevation, 3.7 meters.

A connection was made from **Dutch Harbor** to USC&GS tidal bench mark No. 10, 1948. This mark is located on the eastern shore of Amaknak Island, about 133 feet from south corner of U. S. Navy wharf, 81 feet from north corner of Fleet Post Office (Building 506 in Naval Operating Base), and south of intersection of street leading to wharf with street parallel to waterfront. Bench mark is set one foot in from northern (outer) edge of first step of four-stepped circular concrete base of 100-foot memorial flagpole enclosed by 70 x 125-foot concrete post and chain fence. The gravity meter difference from station **Dutch Harbor** to bench mark No. 10 is minus 1.29 milligals.

Recovered Stations, Alaska

Umiat airstrip. An unmarked station on the south edge of the airstrip, about 150 feet south of the center of the airstrip, 50 feet east of the center of the road leading to the camp and 2 feet below airstrip level. The station corresponds approximately to the base used by the United Geophysical Company and the gravity meter site occupied by G. P. Woollard in 1950.

Point Barrow airstrip. An unmarked station at airstrip level, at the east entrance to the waiting room. The station is about 4 feet below the gravity meter site in the center of the waiting room occupied by G. P. Woollard in 1950.

Geophysical Institute. At the University of Alaska, about 3 miles west of Fairbanks, in the small telephone terminal room in the basement of the Geophysical Institute. This is the pendulum gravity station established by G. D. Garland in 1953 and is the site adopted by the International Gravity Bureau as the Fairbanks station of the fundamental world gravity network. The station is about 80 feet northeast of, and at the same elevation as USC&GS bench mark F 53 1951, located on top of the concrete loading platform at the west end of the Geophysical Institute building.

Latitude, $64^\circ\ 51'.5$; longitude, $147^\circ\ 49'.3$; elevation, 157.1 meters.

Anchorage, Elmendorf AFB, passenger lobby. An unmarked station on the concrete just outside the field entrance to passenger lobby of the MATS and commercial terminal, Elmendorf Air Force Base. The station corresponds to the gravity meter site occupied by G. P. Woollard in 1950.

Unalaska Pendulum (USC&GS, 1938). Near the center of the village of Unalaska, in the southeast corner of the intersection of Bayview Avenue and Second Street, and about 60 feet back from the high water line in Iliuliuk Bay. The station is marked by an 18 x 24 x 40-inch concrete pier projecting about one foot above ground surface, and corresponds to the site used by R. L. Pfau for pendulum observations in 1938.

Latitude, $53^\circ\ 52'.6$; longitude, $166^\circ\ 32'.1$; elevation, 3.7 meters.

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